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Introduction

Since the late 1980s, climate policy debates have been making extensive use of modelling results about the costs of meeting climate objectives. To what extent this use succeeded in rationalising discussions is not so obvious. From the Third Conference of the Parties (COP3) (Kyoto) to the semi-failure of COP6 (The Hague), despite the attempts of the second and third reports of the International Panel on Climate Change (IPCC) to clarify what 'good use' could be made of results discrepancies in designing a viable climate regime (Hourcade, 1996; Markandya and Halsnaes, 2001), it did not manage to create a common understanding between the optimists and the pessimists about the costs of Kyoto targets. It did not succeed either in delivering robust and consensual qualitative insights regarding the policy mix most likely to minimise welfare costs. Ultimately, negotiations were conducted under pure diplomatic rhetoric with almost no link to well-grounded, even though controversial, economic analysis.[2]

Reasons for this communication failure between scientific expertise and public decision-making are many, among which the diplomatic cycles of the climate affairs, the political resistance to some recommendations, and the lack of convincing power of the modelling state of the art—due to some real weak-

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[2] A typical example is the European Union maintaining the 'concrete ceiling' proposal as the cornerstone of its diplomatic position, even though economic analysis reveals that this proposal, aimed at forcing the US to undertake diplomatic action, would have primarily penalized Japan and the EU (Hourcade and Ghersi, 2002).

nesses. However, this chapter starts from the idea that this failure is owed to a great extent to the confusion about the very concept of cost.

The seemingly simple notion of ‘cost’ is indeed deeply polysemous: there is a significant distance between its meaning for the average consumer keeping an eye on the price of petrol, the industry concerned by its competitive position, and the government in charge of the balance of public budgets. There is yet another hiatus between the points of view of any stakeholder and its significance within the theoretical and empirical constraints of modelling exercises, including those set by incomplete data or computational limits.

In this chapter, we first review the cost concepts used both in public debates and in the modelling community. Secondly, we elaborate on the way the apparently tangible concept of ‘abatement expenditures’, which conveys technology assumptions, is translated in partial and general equilibrium models. Thirdly, we place some caveats about how to translate the models’ information on marginal policy costs into policy signals, at various points in time. A last section focuses on the ways and means of the TranSust models to report costs.

I. What costs do we measure? What costs do we discuss?

Economic modelling literature circulates costs assessments that are not directly comparable, simply because they measure different realities, in different metrics and under varying economic, geographic and time aggregations. Combining these three dimensions produces a large number of different cost assessments of the same policy, paving the way to misinterpretations and/or strategic uses of information.

I.1. What type of cost?

Setting aside the accounting of ancillary benefits,[3] the types of costs commonly used to assess climate policies fit into three broad categories.

Technical costs, or direct abatement expenditures, are the main ingredient of the partial equilibrium models detailing energy production and consumption in a technology-rich manner. They are also the main outcome of these models, through the aggregation of the equipment expenditures emerging from a ‘bottom-up’ description of energy systems. In bottom-up models, the choice of supply and demand techniques is quite systematically based on a set of energy prices and investment plus operation and maintenance costs. These prices and costs are expressed in some constant currency, that is (implicitly) relative to a constant price index of the non-energy goods and services. Opposed to bottom-up models, the typical ‘top-down’ macroeconomic models have a limited ability to pinpoint abatement expenditures because of their higher degree of aggregation in the description of energy systems. This level of abstraction is the source of a paramount ‘tangibility issue’ that will further be addressed below.

[3] Measuring ancillary benefits relates to specific methodological difficulties. But these are not a source of confusion *per se* because common practice is to present them separately and subtract them from the other policy costs.

Macroeconomic costs relate to evolutions in total output, consumption or revenues (gross domestic product—GDP). In order to be computed they require a comprehensive description of economic flows. Contrary to direct abatement expenditures, they encompass the general equilibrium effects of the energy systems transformation on the rest of the economy.[4] Capturing such interdependences is critical to understanding why the technical cost of a policy action may not indicate the burden it ultimately lays on an economy.

Welfare costs refer to the economic concept of utility losses, and capture the ultimate impact of policies on the well-being of an economy. In a macroeconomic framework they are typically computed for an aggregated household or 'representative consumer', or through the weighted sum of the utilities of various household classes. Expressed in money metric terms, they provide a comprehensive measure of the social costs of climate policies.

The 'costs' of a given policy can refer to any of these three types. The necessary wedge between the three corresponding assessments obviously causes confusion. It is particularly high between technical costs on one side and macro-economic and welfare costs on the other because of, in a closed economy:

- The structure of the input-output (IO) matrix, or inter-industrial relationships, which determines how the direct price increase induced by technical costs spreads throughout the production system and results in a new set of relative prices.
- The impact of this shift of the price vector on the trade-off between factors in production—and the looping of these two first effects to equilibrium.
- The pre-existing tax system, which both distorts carbon price signals, and offers the opportunity to coordinate climate and fiscal policies so as to minimise the marginal welfare losses of a given climate objective—the 'double dividend' issue (Goulder, 1995; Bovenberg, 1999).

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[4] Another source of misunderstanding, the notion of 'general equilibrium' is often used referring to a situation in which all markets clear through the adjustment of a price vector, leading to an optimal utilisation of resources. But it is also used in opposition to partial equilibrium, indicating that all markets and their interdependences are accounted for. The question is indeed to capture these interdependences, *i.e.* the propagation of 'policy shocks', regardless of whether the economies under scrutiny are optimal or experience transitional or structural disequilibria.

- The functioning of the labour market: the degree of wage flexibility determines how policy-induced changes in the relative price of labour affect the level of employment and ultimately real wages. Real wages in turn impact upon the disposable income and households' consumption.
- Public budget constraints: if a policy is revenue-raising (tax, auctioned permits), how is this revenue recycled? If it requires funding (compensating measures, subsidies, guaranteed prices, infrastructure development and so on), how is it financed?
- The costs of redirecting technical change: to some extent, the investment in abatement activities crowds out general investment and has a negative impact on general productivity, unless one allows for fully compensative spillovers (Goulder and Schneider, 1999).

The interplay between these parameters is further complicated by the insertion of economies in international markets, including those for fossil fuels and in some instances carbon itself. The reaction of oil, gas and coal prices to carbon pricing and the general shift in regional relative prices impact upon the terms of trade, with obvious macroeconomic or welfare consequences. Last, but not least, international financial markets constrain the investment decisions to build new energy capacities—they will play an especially important role in decades to come as energy demand will greatly exceed current supply capacities (IEA, 2003).[5]

An ample literature demonstrates that the impact of these national and international factors is such that they can go as far as overruling the direct effect of the policy. They can turn an abatement cost into a macroeconomic gain—the stronger form of ‘double dividend’ following Goulder's definition (Goulder, 1995)—or, in the opposite direction, exacerbate the social costs of a rather modest policy. Subsequently, the desirability of a policy option can vary widely with the type of cost considered. This probably constituted one of the obstacles to an international agreement in climate affairs: on top of selecting more or less optimistic models to back their positions, advocates and opponents of an active climate policy, even when using the same model, could put

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[5] With the notable exception of the G-Cubed model (*cf. e.g.* Mc Kibbin *et al.*,1999), international financial flows are still dominantly exogenous, determined by the evolution of trade balances.

the emphasis on the type of cost supporting their stance—and disregard the others.

I.2. In what metric?

Another major interpretation problem regards the economic meaning of the metrics under which cost figures, whatever their type, are delivered. The same type of cost can indeed be expressed in marginal, average or total values,[6] and for each of these values in absolute or relative terms. Some of the underlying issues relate to substantive economic questions. Others are again more rhetorical in nature.

I.2.1. Marginal, average, or total cost? The dangers of singling out one indicator

Considering that marginal costs are quite systematically higher than average costs, it is not surprising that the tenants of action against climate change often insist on the latter, while their opponents favour the former. It is obviously possible to limit confusion and provide a sound and policy-relevant assessment by reporting these indicators jointly. Their difference is indeed a good indicator of the convexity of marginal costs around a given abatement target—and consequently of the risk generated by uncertainty: a small (large) wedge between the marginal and average costs means that the marginal cost curve is 'rather straight' ('rather convex') and that, in case of an *ex ante* underestimation of the marginal cost, the extra burden will be low (high).

More generally, there is no scientific conflict behind reporting results in terms of a marginal, an average or a total value. All three metrics matter and should systematically be reported in order to have a precise diagnosis of the impacts of climate policies on an economy. For each of them, it is also important to observe discrepancies in the assessment of the three types of cost introduced above: in most modelling frameworks there is no *a priori* reason why the measures would match. It may happen, for instance, that the steepness of

[6] Some models are designed to deliver the average and total costs, others the marginal cost, but all can produce all three indicators. Depending on the type of model from which they are drawn, though, marginal costs ultimately tend to reflect varying realities. This point will be developed in a further section.

the marginal abatement expenditures curve is higher than that of the marginal welfare curve, depending on the pre-existing carbon intensity of an economy and on the efficiency of tax recycling. To use this information in public debates would facilitate the understanding of how certain policy packages (various forms of carbon trading with or without safety valve, auctioned permits, carbon taxes, compensating transfers, and so on) hedge against uncertainty, both at an aggregate level and for various social groups.

However, policy-makers tend to insist on marginal costs, interpreting them as the carbon price necessary to meet a given carbon target—our fourth section will question this interpretation. The reason for this insistence is obviously the sensitivity of public opinion to energy prices (for example that of petrol), which constitutes one of the strongest acceptability constraints of environmental policies. But focusing on the price of carbon may be misleading, including in political terms: negative macroeconomic or welfare impacts are the potential indicators of social tensions that can ultimately prove as important.

	Carbon price in 2010 (1990 USD per ton)			vs	GDP losses (% BAU 2010 GDP)		
	Highest	Second	Lowest		Highest	Second	Lowest
ABARE-GTEM	Europe (665)	Japan (645)	USA (322)	≠	USA (1.96)	Europe (0.94)	Japan (0.72)
AIM	Japan (234)	Europe (198)	USA (153)	≠	USA (0.45)	Europe (0.31)	Japan (0.25)
G-Cubed	Europe (227)	Japan (97)	USA (76)	=	Europe (1.5)	Japan (0.57)	USA (0.42)
MERGE3	Japan (500)	USA (264)	Europe (218)	≠	USA (1.06)	Europe (0.99)	Japan (0.8)
MS-MRT	Japan (402)	USA (236)	Europe (179)	≠	USA (1.88)	Japan (1.2)	Europe (0.63)
RICE	Japan (251)	Europe (159)	USA (132)	≠	USA (0.94)	Japan (0.78)	Europe (0.55)

Source: drawn from IPCC (2001), p.514

Table 1 Regional ranking in marginal and macro-economic costs of Kyoto implementation, 6 models

Table 1 illustrates this point: for five of the six models reported the ranking of regions from the most to the least impacted, in this example of a

‘Kyoto without carbon trading’ simulation, widely differs whether one considers the marginal cost (carbon price) or macroeconomic cost (GDP losses). Averaging on the available models depicts the USA facing the lowest marginal cost, a perception which lead many to consider that it should embrace an ambitious target; but at the same time the USA faces the highest macroeconomic costs, and this in turn accounts for its negotiation stance. The contradiction is manifest, and partly explains the consecutive negotiation failure.

I.2.2. In absolute or relative terms? A false but important quarrel

A second dimension of the metric in which literature reports results is the precise unit in which the costs are expressed. Three units are mostly used:

- absolute amounts of some currency,[7]
- relative variations of a macroeconomic indicator (GDP, final consumption, and so on) or welfare at some point in time,
- variation of the annual GDP growth rate between the current year and the year for which the policy is estimated.

The choice between any of these three units—again, theoretically legitimate for any of the cost categories—is very strategic in nature: starting from the same modelling exercise, it may give very different views of the economic and social burden of a given policy. It indeed constituted one of the crucial discussions arising when the IPCC had to summarise the findings of its second assessment report (IPCC, 1996): the same 2% GDP loss at a 20-year horizon can be transformed into a daunting figure of billions of dollars if presented in an absolute value, but into an almost negligible 0.1% decrease in the annual growth rate over 20 years as well.

There is probably no way to circumvent these communication biases. They originate in a more fundamental issue, which is the very meaning of a figure such as a 2% GDP loss at a given date (or its equivalent in the two other

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[7] Welfare variations can be converted to money metrics by computing, alternatively, the equivalent variation in income (the variation in income that would induce the same welfare variation as the policy considered under the initial set of prices), or the compensating variation in income (the variation in income that would maintain welfare to its no-policy level under the policy-induced set of prices).

units). This issue matters for the costs of mitigation strategies as well as for those of climate change impacts. Macroeconomic assessments of both mitigation and impacts are indeed of the order of a very few GDP percentage points, with variations from one analysis to the other of quite the same order of magnitude. This may lead the reader to conclude that, all in all, the amounts at stake are quite low. Depending upon his pre-existing intuition, he might conclude that action must be undertaken anyway, or that it is useless to be too concerned—or simply that the meaningfulness of climate policy assessments is to be doubted. After all, as reminded by Hogan and Manne (1977) in a striking 'elephant and rabbit' metaphor, costs cannot but be low, simply because energy represents a minor share of total GDP, and a production factor whose cost share is, for most activities, lower than that of labour or many other intermediary inputs. However, nobody would argue that, because energy is a statistical 'rabbit', the energy system is of second-order importance for the stability and pace of economic growth. In fact, a single aggregate figure over a long time period may hide transitional economic costs high enough to induce social and political deadlocks.

To avoid the trap of a quarrel about metrics, the focus should thus be placed on understanding the mechanisms that govern the magnitude of costs, and on the reasons why different policy packages may incur costs separated by a factor of two or three—some of them even changing the very sign of the net outcome in terms of welfare or total income. To debate whether 1% of GDP is too high a cost is far less useful than to understand why this 1% can alternatively be turned into a 2% cost, or indeed a 0.3% gain, by different policy designs.

I.3. Under what aggregation?

I.3.1. A static aggregation of sectors, regions and households

Paramount policy questions are related to the distributional effects of climate policies on regions, industrial sectors or households. In this regard, the information critical to interpreting the economic meaning of modelling results is the implicit or explicit aggregation principles retained in the models, and the corresponding implicit or explicit compensations. It is very unlikely indeed that climate measures will have evenly distributed effects on regions, individuals or economic sectors: when a 2% loss is reported, this loss is an aggregate measure of variations in income where some may gain and others loose more that 2%. In this respect, a distinction has to be made between the aggregation of sectors and the aggregation of regions and households.

Concerning industry, the higher the level of aggregation, the higher the risk that models overlook how some sectors could suffer from policy-induced shocks too strong to be immediately absorbed in the absence of appropriate accompanying measures. This is a problem of technical limitation rather than one of confusion in the cost concepts or of biased results communication—we will consequently not further discuss it.

Turning to regions and households, the measurement of welfare variations through an aggregate indicator relates to a more fundamental problem. The basic raw materials of welfare assessment (setting aside variations in environmental amenities) are households' income and consumption. But aggregate income or consumption are weak indicators of welfare variations, simply because the utility of a €1 gain or loss is not the same for someone who hardly fulfils their basic needs or for the higher incomes. This difficulty appears whenever one wants to measure the aggregate welfare variation of a group of households or regions from models providing household or regional disaggregations. It is solved by selecting 'weights' to ponder each household category's or each region's welfare.

The first reflex, common for non-economists, is to use the same weights for all household types or regions, as would appear ethically legitimate. But, maximising total welfare on such a basis causes a huge movement of income distribution: with the marginal utility of revenue decreasing, minimising the aggregate welfare impact of any environmental policy (in fact of the provision of any public good) results into placing its burden on the richer classes only until *per capita* incomes are equated. Such a strong egalitarian principle is a matter of ethical and political values; it would be both unrealistic and ethically questionable to adopt it 'in passing', at the occasion of environmental or energy policies Another possibility, retained in optimal control models with several regions, is to resort to Negishi weights, which are roughly inversely correlated to *per capita* incomes at each point in time (see for example the description of RICE in Nordhaus and Yang, 1996). Doing so imposes a form of 'no redistribution constraint', but at the cost of considering the current and projected distributions of income either as optimal or as unchangeable.

In fact, most general equilibrium models do not directly address distribution issues. Consequently, to avoid misinterpreting an 'x% of something' figure, it matters to pay due attention to the fact that this figure is true under two important conditions: the first, rather conservative but politically realistic, is that the individuals and countries forming aggregates are implicitly weighted in function of their revenue (because they represent a higher share of total consumption); the second, more problematic, is that appropriate compensating measures are implemented to moderate the distributive effects. In the absence of such measures, an aggregated figure may mask significant shocks on some portions of the population or of the productive activity, potentially great enough to undermine the political acceptability of climate policies.

I.3.2. A dynamic aggregation over time periods

Although the costs of climate policies span over years, policy-makers need cost assessments in a form compact enough to be usable in a policy debate. Their need is addressed under two main modalities. The first is a cost at a given point in time, for example a given percent of GDP loss or a price of carbon in 2012. The second is a discounted sum of costs (whatever their type) over some time period.

The overdominance of these two modalities comes from their apparent simplicity. However, the 'point in time' figures may mislead the comparison of carbon control policies: the policy with the lowest cost at a given date may require a costly acceleration of abatement investments beyond this date. Notwithstanding the long-lasting debates on the appropriate discount rate (see for example Portney and Weyant, 1999; Newell and Pizer, 2001), the 'discounted sum' modality does not present this inconvenience and provides an aggregated indicator, which encompasses all the time periods of the control policy. But the price to pay for this aggregation over time is to lose track of the time profile of costs, making it impossible to detect whether a given policy confronts dramatic peaks in its costs at certain periods. As a striking example, the GDP loss of the First World War for France, with 1.5 million men killed in action (from a population of 40 millions) is estimated at only 0.2% of its aggregated 20^{th} century GDP. As long as economic analysis does not provide a convincing evaluation of the difference between the same GDP loss resulting from: (*i*) a cumulated constant difference between two steady-growth pathways over some extended time-period; and (*ii*) a 'point' shock on growth concentrated on a short time period, it will be important to supplement the discounted costs assessment by some information on the cost profiles.

Many models are not suited to the in-depth study of such profiles: static general equilibrium models can only report them in a limited way, assuming a smooth and steady transition from the supposed date of the policy implementation to the new equilibrium; recursive models often exogenise the time profile of either the price signal or the emission constraint to derive cost profiles. The models intrinsically suited to studying cost profiles are the optimal control models: their inter-temporal decision framework allows them to shift the emission constraint to concentrations or temperature increases—derived from simplified climate modules—thus endogenising both the abatement efforts and the corresponding marginal cost constraints. It is consequently intriguing that they should not be more often applied to richer thought experiments, for example climate policies delayed until some time threshold where new information requires acceleration (Ambrosi *et al.*, 2003).

II. The crux of the matter: conveying technical information in an economic analysis

Among all the measurement issues discussed above, those related to temporality and metric do not raise any problem that cannot be settled through a careful presentation of results delivering the full set of available indicators. The choice of a type of cost is a much harder nut to crack, as there seems to be a fundamental asymmetry between the tangibility of the notion of 'total abatement expenses', and the theoretical taint of an indicator such as 'total welfare variation'. At a purely scientific level, the core of the matter ultimately hangs on the ability of models to reproduce technical realities, which in turn fundamentally determine the responsiveness of economies to carbon constraints. It is thus important to clarify how technology is described in the various modelling paradigms at hand—this will allow an understanding of why bottom-up analysis does not suffice in providing sound answers in the absence of coupling with general equilibrium analysis.

A first way of representing the techniques that shape the cost of carbon constraints is indeed through the description of ***explicit detailed equipment stocks*** in the production and consumption of energy. Such a description is characteristic of bottom-up models, which picture a set of competing equipments identified by their investment, operation and maintenance (O&M) costs, their productivity (in terms of energy services for consumption equipments) and their lifetime. At each period, the scrapping of the existing equipment and the evolution of demand define the need for new capacity. A straightforward cost-efficiency analysis determines which equipment should address this need. Technical progress can be accounted through an evolution of each equipment's characteristics, endogenous or not—some bottom-up models currently feature learning-by-doing (LBD) processes in some way, correlating the investment and O&M costs of an equipment to its market share.

Explicit information about the cost-performance ratio of techniques is thus the ‘raw material’ of this type of model, from which the most famous types of marginal abatement costs curves (MACCs) are derived. With abatement on the abscissa and marginal cost on the ordinate, these MACCs are generally formed of an ensemble of plateaus, linked by ‘stairs’ that are rather shallow for low levels of abatement (sometimes with negative costs), become higher as abatement levels increase, and usually end in some form of vertical asymptote: carbon prices tend to the infinite beyond a certain abatement threshold. This engineering-based information is explicit, and easily translated in a very tangible implication: the amount of expenses necessary to a given amount of abatement. However, this should not mask that the MACCs derived from such analysis are also modelling constructs:

- They reflect controversial sets of hypotheses given by technology expertise about negative cost potentials, incremental technical progress and breakthroughs, and so on. These hypotheses interact in more-or-less aggregated technical subsystems that can be highly complex, as refineries or electric networks.
- Bottom-up analysis still often represents the adoption of technology as ‘knife-edge’ economic optimisation, in a linear optimization framework where the shift from one corner solution to another one can be quick. In most models this instability is controlled, but at the cost of modelling artefacts as *ad hoc* limitations to the penetration rate of techniques. Elements such as market barriers, hidden consumer preferences, the dif-

ficulty of economic agents to form long-run expectations in a volatile context, and so on, are yet seldom represented.

- In reality, technical costs are determined by the quantities and prices of intermediary inputs and primary production factors, which are not so easily observable. For instance, in long-run studies the price of bio-energy cannot but depend on the costs of land, labour and transportation and delivery activities, which themselves depend on the scale of production. Bottom-up MACCs are thus conditional upon a set of generally implicit assumptions guaranteeing the precise non-energy price vector considered in their analysis. For the higher carbon constraints, this vector of relative prices may change drastically if compared with that implicitly or explicitly employed, possibly threatening the relevance of bottom-up estimates.

- The carbon price ultimately leading to a certain level of abatement is the price that induces this abatement once all the economic adjustments have operated. As demonstrated by a numerical experiment between IMACLIM and POLES, the wedge between the pre- and post-adjustment prices may be high (Ghersi *et al.*, 2003).

Macroeconomic models address the two latter issues by extending model coverage to all economic flows, at the price of more compact representations of techniques. Thus, they limit the level of detail of the description of technical systems and resort to ***aggregate production and utility functions*** as proxies to the real technical flexibilities. The typical multisectoral general equilibrium model thus pictures a number of goods—among them one or several types of energy goods—that compete, to some extent, as: (*i*) intermediate consumptions in all productions; and (*ii*) final consumptions for the households. These two competitions are driven by the evolution of the relative prices following substitution elasticities, in more or less complex 'nesting' structures: selected goods compete to form a bundle, which in turn competes with other bundles or goods to form a higher-level aggregate, and so on, up to the output or utility. At each tier of the corresponding tree, different substitution elasticities (possibly nil, under a Leontief assumption) allow enhancement of the match between the model and the realities it is trying to render. As regards production, technical progress typically impacts upon this structure as one or several multipliers applying to some or all factor consumptions; the evolution of these multipliers can be either exogenous or endogenous, with varying specifications in the latter case (LBD, correlation to R&D, to gross investment, and so on). Some models account for another form of exogenous technical progress through the specification of a 'backstop' carbon-free energy technology; the assumptions regarding the cost dynamics of the backstop obviously play a paramount role in the assessment of the higher carbon constraints.

A third option, at the same level of aggregation as the second, submits the dynamics of input-output structure to ***econometric analysis*** rather than to production and utility functions. Its main advantage is to relax the constraints imbedded in the functional forms commonly used by macroeconomic models, mechanically enhancing the ability to replicate observed flexibilities. However, econometric specifications are usually estimated on one precise consumption (in economy-energy-environment models, that of energy) and tend to ignore substitution effects.

At the higher aggregation level, optimal control models describe a single-agent ('benevolent planner') economy, in which a production function of primary factors (K, L, and possibly but not necessarily some energy goods) approximates all production technologies. Such a high level of stylisation gives the possibility to explore longer terms, over which the basket of technologies cannot be described explicitly—an interesting feature when it comes to carbon policies, considering the inertias involved. On a more pragmatic note, it facilitates calibration, and significantly enhances computation ability, allowing the implementation of inter-temporal optimisation over a large number of periods. As a negative consequence, though, its results cannot be linked to an explicit evolution of the energy systems in the short or mid-term; how relevant they are regarding this evolution relies on the specifications governing the decreases in energy or carbon intensity—a representation of ***technologies by paralipsis***.

As is seen from these descriptions, each of the four options to technology description has its pros and cons. To begin with the pros, they all address quite different questions in a satisfactory manner. As for the cons, on the one hand, even the most tangible bottom-up approach, notwithstanding its fundamental partial equilibrium limitations, can be criticized on account of its describing the adoption of new technologies as some cost-efficiency analysis, bypassing the complexity of consumers' preferences as expressed in documented adoption patterns. On the other hand, the more aggregated approaches with implicit technology all suffer, to some extent, from their inability to reproduce technical options and constraints faithfully—a major constraint being the existence of asymptotes to the decreases in energy or carbon intensities, at any given time horizon. Particularly, their treatment of substitution possibilities is inadequate when it comes to households, whose energy-consuming equipment (transportation and residential sectors) is rarely identified, despite its paramount importance in emissions trends.

In a nutshell, there is an obvious need for research devoted to modelling frameworks that allow for an easy back-and-forth reflection from technical realities to integrated price-and-quantities economic analysis. A way out of this deadlock could be hybridisation.

III. From costs to policy signals: a sometimes too hasty translation?

As already hinted, all the nuances brought up in the previous sections are mostly overlooked, not only in the political sphere, but also to some extent in academic circles. Throughout the years, the most successful indicator remained the marginal cost and it is a matter of fact that, whatever the underlying modelling paradigm and the type of cost thus measured, it is often interpreted as the level of price-signal that should be given to agents to achieve a certain environmental objective in a decentralized economy. This rather intuitive interpretation is sometimes correct; but in most cases it should be qualified with some caveats, to say the least.

Let us start wit a reminder that, from an economic perspective, any form of marginal carbon cost boils down to the shadow price of some form of carbon constraint, that is, the monetary or welfare costs of strengthening the constraint by one unit. In a dynamic setting, this shadow price exists at any modelling period, from the benchmark year to the projection date. It is explicit in optimisation models, and can theoretically be revealed in any other modelling framework. Starting from there, how far its interpretation can legitimately be stretched in terms of policy signal demands a more in-depth examination.

First, there is no necessary equivalence between the marginal income loss and the marginal value of abatement expenditures (mostly conveyed through a carbon price). To convince oneself of this, suffice it to notice that implementing a carbon constraint in a hypothetical economy without technical flexibility would lead to nil abatement expenditures, but surely to an income loss. On top of this, the body of general equilibrium effects detailed in section I.1 determines the wedge at each point in time between the carbon price implied by the required abatement, and the marginal income or welfare losses. The distinction is obvious, if rarely underlined: it is proven by the mere fact that, in the case of a carbon tax, welfare results vary widely with recycling assumptions, as was extensively demonstrated in the exploration of double-dividend issues—the following section will exemplify this with the results of the policy runs performed by TranSust modellers during their collaboration. Prominent reviews, though, report both the marginal abatement costs from bottom-up models and the marginal income losses from integrated general equilibrium analyses (IPCC, 1995; IPCC, 2001). This facilitates the perception that the two notions provide equivalent information about the necessary carbon tax.

Second, the preceding discussion does not incorporate the signalling effect of prices. It is conducted in a static framework, where the abatement cost curve is given, and the carbon price set at the level corresponding to the required abatements. Without entering the difficult discussion of optimal pricing under an induced technical change framework, let us illustrate the point in the case of optimal control models. In such models a wedge may exist between the shadow price of the constraint and the optimal price signal that should be delivered, due to fundamental inter-temporal issues. To understand why, let us consider the two time profiles of marginal abatement expenditures and marginal income losses: they are indeed strictly equivalent in models where there is no source of path-dependency between abatement costs at a given date and abatement volumes in the previous periods. But assuming such independency amounts to disregarding the inertia of capital stocks, or learning-by-doing processes—a quite unrealistic stance. Under a more plausible description of technical dynamics, the two profiles do not necessarily match anymore: assuming perfect foresight, the 'benevolent planner' considers the entire set of future carbon prices; because of the path-dependency in abatement costs, at each period he decides more abatement expenditures than he would do according to the shadow price of the constraint—variation of the discounted sum of utility along the optimal response pathway up to an infinite horizon. This is due to the fact that, because of inertia in the return of these expenditures in terms of greenhouse gas (GHG) abatement, these expenditures have to be made earlier than they would be in a totally flexible world. Spending more at t indeed allows lowering adaptation costs for carbon constraints after $t+n$. The amount of this 'excess expenditure' is directly correlated to the level of inertia in the economy. Now, let us assume the same economy with myopic expectations and the necessity of public signal to correct this myopia. Should a policy-maker interpreting such results set the time profile of price signals to match that of the marginal abatement expense, or that of the shadow price of the carbon constraint? If he does the latter, myopic agents will under-react. The problem appears dramatically in optimal control models in which heterogeneous sectors are represented; the optimal policy indeed implies spending a far higher amount of expenses on a sector as rigid as the transportation sector in the early periods, when the low level of carbon taxes would imply only marginal departures from baseline. Conversely, should a carbon tax be set at the shadow price of the carbon constraint, and should the economic agents involved in this sector behave myopically, the transportation sector would under-react, with consequences falling on the entire economy (Lecocq *et al.*, 1998).

There thus appears a policy issue about how to handle 'signalling' deficiencies: is it necessary to set differentiated carbon taxes or carbon taxes complemented by other incentives in the rigid sectors? Is it possible to count on an upgraded credibility of the announcement of carbon prices over the long run, so that economic agents work under prefect expectations in this domain? So far, empirical models have not been much used to explore such debates, although they do incorporate some information to do so.

A final *caveat* must be placed on another source of gap between the carbon price signal and the marginal social cost at a given point in time: the possibly strong importance of prices other than that of carbon. One simple example is the shadow price of imports: minimising the price of carbon through trading systems, for example by importing tradable emission permits, will induce huge imports that can be a significant political obstacle for some countries (this is one of the arguments of the opponents to Kyoto in the United States). Another example is again related to transportation dynamics. It has been explained why this sector 'should' devote more abatement expenses than those resulting from the shadow prices of carbon during the first decades of a climate policy. However, it is unlikely that any politician will ever take the risk of raising the ‘required’ levels of carbon taxes on petrol in the early periods; it is also unlikely that decision-makers in this sector will easily internalise the perspective of ever-increasing carbon prices and launch the corresponding adaptation measures (R&D, investment on public transport, switch to oil-free motor fuels, and so on). This should not suggest jumping too quickly to the conclusion that carbon control in the transportation sector is a form of oxymoron. For historical reasons, existing models concentrate on the energy sector and represent transportation as one subdivision of energy demand. The consequence is that they incorporate the price of carbon as the only driver of consumption and technology choices. This is a reasonable simplification for the electricity sector, heating and industrial processing, but in the case of transportation it may be misleading: it is obvious that the demand for mobility, stemming from the location choices of households and firms, is governed not only by transportation costs but also by real estate prices. In other words, when models conclude to the necessity of a certain amount of abatement in the transportation sector, the incentive to reach this amount may be a mix of carbon prices and of policies aimed at controlling the price of the square meter. Carbon prices may thus not be the only signal triggering the appropriate profile of abatement efforts; a far larger set of price signals should be mobilised.

IV. Cost concepts in the TranSust models

The TranSust models provide quite a representative sample of the modelling approaches and publication practices of the energy-environment-economy community. The following tables summarise how they represent costs in three broad categories: Tables 2, 3 and 4 respectively echo sections I.1, I.3.2 and II, by detailing what type of cost, under which temporality, and based on which technology representation, each model is able to deliver.

	Abatement expenses	Macroeconomic costs	Welfare costs
MULTIMAC	n.a.	available	n.a.
DART	n.a.	available	available
DEMETER	n.a.	available	available
E3ME	n.a.	available	n.a.
FEEM-RICE	n.a.	available	available
GAIN	available	available	n.a.
IMACLIM	available	available	n.a.
MARKAL	available	n.a.	n.a.
MIDE	n.a.	available	n.a.
PACE	n.a.	available	available
W8D	n.a.	available	n.a.

Table 2 Types of costs available from the TranSust models

As regards the types of costs reported, the panel of TranSust models expresses the current dominance of the macroeconomic approach to E3 modelling (Table 2). A piece of information not appearing in the table: it happens that the models reporting macroeconomic costs are quite evenly divided between macroeconometric models (E3ME, GAIN, MIDE and W8D), and the other approaches. This strongly impacts the number of models able to deliver welfare variation estimates, as by definition macroeconometric models do not resort to utility functions to describe household preferences, and hence cannot produce them. MARKAL alone truly belongs to the bottom-up category, which allows it to deliver precise abatement expenses assessments. GAIN and IMACLIM only give elements thereof, either at a quite aggregate level (GAIN), or through a soft-linking with an energy systems model (IMACLIM runs coupled to POLES, a model of prospective energy systems—*cf*. Criqui, 2001).

	Point-time estimate	Discounted sum	Cost profile
MULTIMAC	available	n.a.	n.a.
DART	available	n.a.	n.a.
DEMETER	available	available	n.a.
E3ME	available	n.a.	n.a.
FEEM-RICE	available	available	available
GAIN	available	n.a.	n.a.
IMACLIM	available	n.a.	n.a.
MARKAL	available	n.a.	n.a.
MIDE	available	n.a.	n.a.
PACE	available	available	n.a.
W8D	available	n.a.	n.a.

Table 3 Costs temporality in the TranSust models

As is the case for cost types, cost temporality is dominated by one of the three distinguished modalities, that of point-time estimates (Table 3). Only three models resort to inter-temporal optimisation, and thus naturally integrate the discount rates necessary for computing discounted sum estimates. Then, FEEM-RICE alone is able to endogenise (in this instance optimise) cost profiles to attain a given climate target at some horizon. This is partly correlated to the degree of sectoral and regional aggregation, as FEEM-RICE and DEMETER respectively picture a single region and a limited number of commodities, and a single commodity and a limited number of regions. But as regards the point-time/discounted sum distinction this is also a matter of theoretical stance concerning expectations: PACE and DART, typically, are models of a similar structure (CGE) and scope, but respectively consider perfect versus myopic expectations.

	Explicit equipment stocks	Production functions as proxies	Econometric analysis	By paralipsis
MULTIMAC		X		
DART		X		
DEMETER		X		
E3ME			X	
FEEM-RICE				X
GAIN			X	
IMACLIM		X		
MARKAL	X			
MIDE			X	
PACE		X		
W8D				X

Table 4 Technology representation in the TranSust model

Turning to what we described as "the crux of the matter", Table 4 characterizes the representation of technologies in each model, along the four broad categories depicted in section II above and their increasing level of abstraction. At one hand of the spectrum, MARKAL alone explicitly details concrete equipment stocks that can be characterized according to the particular focus of each analysis. At the other hand, FEEM-RICE and W8D, although of a thoroughly different nature, share a similar level of abstraction: they both aggregate all economic activity in a single good, whose production is based on a trade off between primary factors (capital and labour) only; the link to explicit technologies is thus difficult if not impossible to make. In between those two extremes, the majority of TranSust models disaggregate economic activity in a number of sectors, and either resort to production functions or econometric analysis to describe changes in the corresponding input-output relationships. The 'production function as proxy' paradigm can be argued to be slightly less abstract than its counterpart in the sense that it entails explicit substitution patterns, rather than allowing an independent variation of input volumes.

As another illustration of the preceding sections (namely section III), the following graphs describe how the marginal costs estimates differ from carbon prices inputs, in the case of the sample runs performed by each modelling team at the occasion of TranSust. For the mere sake of readability, models are grouped according to the only scale of their macroeconomic impact assessment. Figure 1 and 2 report marginal GDP costs in regard of the carbon taxes corresponding to the five scenarios tested—a general carbon tax linearly increasing from the year 2000 to resp. €10, €20, €30, €50 and €100 *per* metric tonne of CO_2 in the year 2050. Because of the different time horizons of models, Figure 1 presents 2015 estimates, Figure 2 presents 2030 ones.

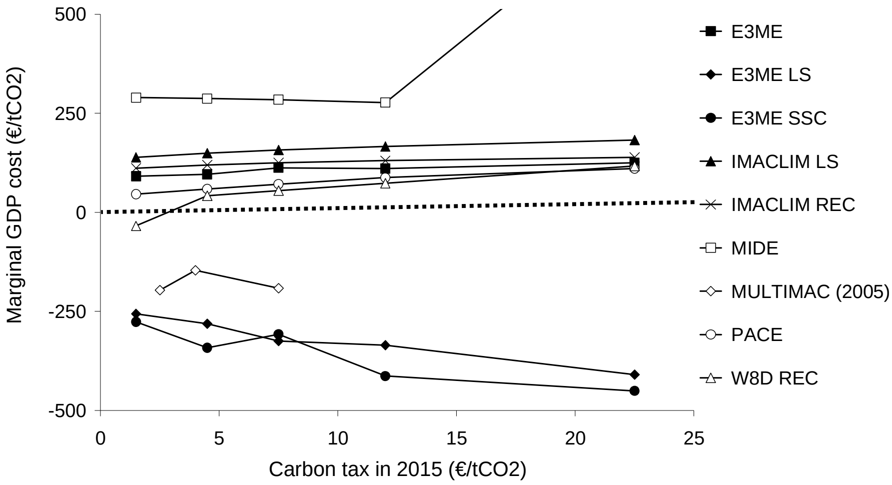

Figure 1 **Non coincidence of carbon tax and marginal macroeconomic costs (1)**

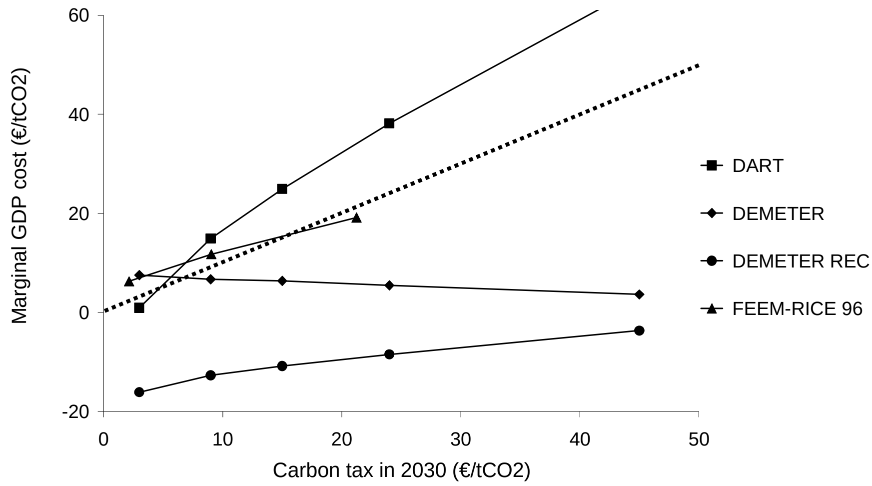

Figure 2 Non coincidence of carbon tax and marginal macroeconomic costs (2)

On both graphs, the dotted lines figuring the Identity function $f(x) = x$ make the general point obvious: in most instances the carbon price input, or marginal abatement cost, widely differs from the modelling output of marginal macroeconomic cost. Indeed, for the same model and an identical tax, different recycling options such as through a lump-sum transfer to households (LS), or a decrease of social security contributions (REC, SSC) lead to cost estimates that can go as far as differing in sign.

Conclusion

Reporting the costs of carbon policies is currently made under the threat of a sequence of two sources of bias. The first is the very nature of the model from which the cost estimate is extracted. Three broad modelling paradigms—the disaggregated technology-rich bottom-up model, the multisector top-down model (be it based on welfare and cost optimisation or on econometrics) and the single-agent optimal control model—are indeed either inclined or intrinsically limited to provide different types of cost, in close connection with the way in which they account for production and end-use technologies. When attempting to compare the meaningfulness or legitimacy of these types of cost, a manner of trade-off appears between 'explicitness' (how easy is it to embrace the explicit expenses summed up in these costs?) and 'comprehensiveness' (to what extent do these costs express the full economic burden of a carbon policy?), which necessarily leads to the conclusion that all three assessment natures should participate to the careful weighing of any policy proposal. Care should be taken, though, to stop confronting cost estimates pertaining to different modelling paradigms, as has in some instances carelessly done. Different modelling paradigms simply do not and cannot provide estimates embracing the same realities and must be used in a complementary rather than comparative manner.

A second source of bias lies in the choice of a reporting template, that is in the manner in which modelling results are eventually summed up. The number of dimensions to this choice opens a wide range of possible templates and offers the tantalising possibility of shaping a message consistent with any *ex ante* conviction, be it optimistic or pessimistic. Clarifying the comparison of two cost assessments expressed in different metrics does not raise conceptual difficulties: it simply requires translating costs assessments in metrics other than that of the original work. The obstacle is pragmatic in nature, as in most instances such a translation cannot be done *ex post*, that is, without rerunning the model that produced the assessment—an option seldom available.

Under this double threat, communicating the costs of climate policies appears quite a challenge, to both the scientific and decision-making communities. On the one hand, experts should bring out rather than hush up the complexities exposed in this chapter, obviously taking the greatest care, in the act, to avoid raising more confusion than they dissipate. On the other hand, the decision-making community should accept that the answer to the question they raise is fundamentally more complex and less straightforward than they would want it to be, on the simple ground, ultimately, that it is manifold in itself.

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